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THE STATUS OF THE LAMPF CONTROL SYSTEM UPGRADE*

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Abstract

The upgraded Los Alamos Meson Physics Facility (LAMPF) control system is now operational. The SEL-840 computer has been removed, and all application programs are now running on VAXes. We are continuing to upgrade the control system network. We are using MicroVMS systems for distributed local control and have introduced VAXELN systems for dedicated real-time situations. Communications with both systems is based on a standardized remote procedure call interface. We have also begun to integrate the Proton Storage Ring controls with the LAMPF control system, to experiment with VAX/GPX-based workstation operator interfaces, and to investigate possible applications of artificial intelligence technology.

## Background

The Clinton P. Anderson Meson Physics Facility (LAMPF) is operated by the Los Alamos National Laboratory for the U.S. Department of Energy. The heart of the facility is a 1-kilometer-long linear accelerator designed to provide a proton beam of up to 800 MeV and one milliampere average current. The accelerator is a pulsed machine operating at 120 Hz.

## Brief Review of LAMPF Control System Upgrade

LAMPF was one of the first major accelerators to be designed for computerized control. The original control computer was a System Engineering Laboratory SEL 840. All access to accelerator data was through a locally designed, distributed, module-oriented hardware system called RICE (Remote Instrumentation and Control Equipment). From the beginning the control system was in a continuous state of modification and upgrade. To improve the SEL 840's performance, memory was increased from 48K words to 128K words, disk storage from 3 Mbytes to 120 Mbytes, and special hardware instructions were added to the SEL 840 CPU. CAMAC devices were added to the system to complement RICE (two local U-type crates, and two serial crates). Eventually a network of four PDP 11/10 remote minicomputers, each with its local CAMAC crates, was added to improve local real time response for certain functions and off-load the main computer. The PDP 11/10s functioned primarily as slaves to the master SEL 840. Communications were through a locally-designed CAMAC-based hardware interface, and local communications protocol. By 1978 the control system provided access to approximately 4000 commandable devices and 10,000 to 12,000 data points. Ninety percent of the devices were accessed through RICE, and perhaps ten percent through CAMAC (local, serial and remote). Figure 1 shows the control system as it appeared in 1978 before the start of the control system upgrade project.

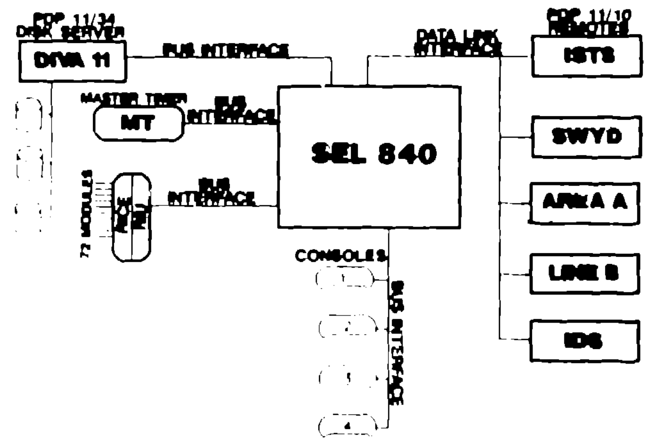


Figure 1 - LAMPF Control System in 1978

About this time it became obvious that the SEL 840 was approaching the end of its operational life.

- It was becoming increasingly difficult to maintain the hardware and find trained maintenance staff. The SEL 840 was no longer being manufactured. Only a relatively small number of machines had been produced in the first place, and modifications to the LAMPF SEL 840 had turned it into a unique computer.

- Growth in the control system created increasing demands, but there was no practical way to further increase the performance of the SEL 840, and no upgrade path to a more powerful machine of the same architecture, since none had ever been produced.

- Without a backup system, any hardware problems in the SEL 840 brought the entire control system down until the control computer could be fixed. Computer problems shut down the control system for extended periods of time (more than a day) on several occasions.

- The relatively primitive architecture of the SEL 840 provided little in the way of program or operating system protection, and allowed bugs in application programs to destroy other programs or crash the entire system.

- The system and application software for the SEL 840 was also difficult to maintain. The entire operating system and all the application programs for the SEL 840 were written by local programmers. Much of the coding was done in assembly language, modern software engineering techniques were not used, and documentation was poor.

In order to deal with these problems, and allow for future expansion, it was decided to upgrade the LAMPF control system by replacing the SEL 840 with a Digital Equipment Corporation VAX

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11/780. This had to be done while maintaining the normal accelerator production schedule. In order to use the VAX 11/780 as the control system computer the following tasks had to be accomplished:

- Interface the VAX 11/780 to accelerator data. This includes RICE, CAMAC, and the network of remote PDP 11/10 systems.
- Interface the VAX 11/780 to the operator consoles.
- Write the system software needed to support real-time control system functions not supplied by the general purpose VAX/VMS operating system.
- Redesign and rewrite the software providing the interface between application programs and the accelerator hardware. We call this software the Data System. The primary goal of rewriting the Data System was to provide greater uniformity in dealing with different types of hardware, and greater flexibility, maintainability, and hardware independence than before.
- Redesign and rewrite the graphics package to support a new set of graphics devices, and also support the old Tektronix 611 storage scopes from the VAX 11/780.
- Redesign and rewrite all the control system application programs to run on the VAX 11/780.

The strategy adopted by the control system section in order to accomplish these tasks was to first build intelligent gateways to the RICE system, and the PDP 11/10 network. This would give both the SEL 840 and the VAX 11/780 access to all the hardware devices on RICE and CAMAC while the conversion was taking place. Then functions could be shifted from the SEL 840 to the VAX 11/780 as manpower and the production schedule allowed. In 1979 the VAX 11/780 was purchased, and by 1981 the control section was heavily involved in the conversion project (it took more that a year to free up the manpower needed to start serious work on the project).

In 1981 the control system software section was staffed by six full-time staff members, and one half-time programmer. The section reached a maximum size of ten staff members and one half-time programmer in 1985. It now consists of seven staff members, and will probably remain at about this level.

The upgrade project has been discussed at several conferences and numerous papers have been published (see references [1]...[13]). At this point we would like to describe the current system, and review some of the future possibilities for the LAMPF control system.

## Current Status of the Conversion

In January of 1987 the SEL 840 was rolled out the door of the computer room and the first phase of the upgrade procedure was complete. The upgraded control system is now operational, running all required application programs. The new system was used to tune and run the accelerator over the last year without any significant problems.

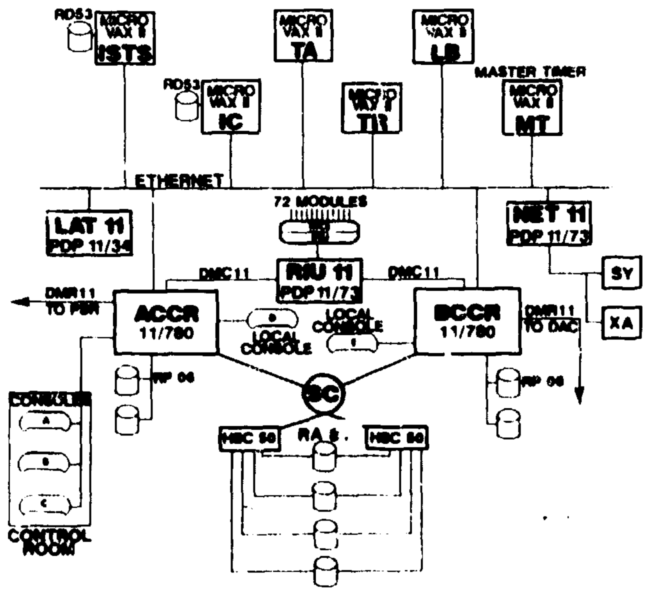


Figure 2 - LAMPF Control System in 1987

## Description of Current System

The current control system configuration is shown in figure 2.

## Main Control Computers

The main control system is a dual VAX 11/780 VAX cluster. One VAX (ACCR) is used as the main control computer with three fully configured operator consoles, and one partial console directly connected to it. The other VAX (BCCR) is used as a backup control computer and program development computer. BCCR has one partial console directly connected to it. Other than the console connections, the 11/780s are identical.

Each 11/780 has 16 Mbytes of memory, 340 Mbytes of local disk storage (2 RP06s), and access to 1,782 Mbytes of shared disk storage (4 RA81s) through the 70 megabit CI bus and dual HSC50 cluster disk controllers. The system disk for each computer is a local RP06, with the other local disk used for online system backups, and as a live spare. Two of the RA81 disks contain all the files used by the LAMPF Control System (LCS). One RA81 contains a backup system disk that can be used to boot ACCR or BCCR and some user directories, and the fourth RA81 is a live spare.

Each computer has access to the RICE system through a one megabit DMC-11 point-to-point link to the RIU11. DECnet running over Ethernet is the LAN for the control system. It provides access to the old PDP 11/10 remotes through the NET11, access to a number of new MicroVAX II remote systems, and access to virtually all other computers on the LAMPF site including the experimental area computers.

Either ACCR or BCCR can perform all the functions needed to tune or run the accelerator. They both have access to all available accelerator data through the RIU11, the NET11, and the new remote computers. They both have access to all needed control system files through the shared cluster disks. Although ACCR normally supports the three full operator consoles in the control room, the consoles can be easily moved to BCCR by shutting down both systems, moving some cables, and rebooting. The procedure only takes about 30 minutes. This design provides a great deal of hardware redundancy for the computer systems. The LCS can survive multiple computer hardware failures, and continue to run the accelerator. At the worst, a reboot may be required to reconfigure hardware/software.

## Gateway Computers

The RIU11 is a PDP 11/73 running RSX-11M, which acts as an intelligent gateway to RICE for both VAX 11/780 control computers, and before it was removed, the SEL 840. The RIU11 does not support DECnet. DECnet can not support the data rates required by the RICE system. Instead, we use locally written device drivers to support our own software protocol over DMC-11 point-to-point links.

The NET11 is a a PDP 11/73 running RSX-11M-PLUS, which acts as an intelligent gateway to the old network of PDP 11/10 remote computers The VAX 11/780 control computers access the NET11 through DECnet over Ethernet links. The data rates for the remote PDP 11/10 computers are an order of magnitude less than those for RICE, well within DECnet capabilities.

## New Remote Computers and Remote Procedure Calls

Early in the control system upgrade we decided to adopt a "standard" remote computer system to replace the existing network of PDP 11/10s, and to be used for any "new" remote computers required by the control system. When we looked at the requirements for new remote systems, we found that we really needed two different kinds of remote computers.

- VAXELN Remotes. These systems are usually in an environment that makes use of a local disk impractical. They have no local operator interface, and function primarily as slaves to the main control computer. They perform dedicated data aquisition and control tasks, often at interrupt level. The standard device interface is CAMAC. The old PDP 11/10 systems all fall into this category. The new standard remote for this type of system is a diskless MicroVAX II computer running DEC's real time control system, VAXELN. MT1, the control computer for the new LAMPF master timer, was the prototype for a standard VAXELN remote. The TR, TA, and LB were converted to VAXELN MicroVAX II systems during the last year.

- MicroVMS Remotes. These systems are really full fledged control systems, but on a small scale. They need an operator interface, and local access to some limited set of hardware devices. Again, the standard device interface is CAMAC. They may need to get data from other remotes, or the RICE system. The main control system may need to access their local hardware devices. The new standard remote for this type of system is a MicroVAX II computer with one or more local disks. The operating system is MicroVMS. A standard operators console is used as the operator interface. The standard LAMPF Control System software can be used without modification. The control system for the Ion Source Test Stand (ISTS), and the Polarized Injector (IC) control system are examples of this type of remote. Both systems were completed early this year.

By using a MicroVAX II for both types of remotes we gained a number of advantages:

- We have only one computer architecture, and two operating systems for the entire control system.

- It is very easy to add MicroVMS remotes to the control system. Because we can use the standard LCS software and application programs, we usually only need to define the new hardware devices to the data system.

- The MicroVAX II is a very flexible and cost-effective system. The remote computers vary widely in the computer power they need to perform their functions. The MicroVAX II is powerful enough to meet the current needs of our high-end remotes, while being inexpensive enough to use for our low-end remotes.

- The MicroVAX II is the most common computer used at LAMPF. It is the standard "Data Aquisition" computer for experiments. This simplifies maintenance support. It is easier to keep adequate levels of spares, and even spare computer systems.

Along with the new standard remote hardware, we adopted a new software convention for communications between remotes, and between the main control computers and remotes. The software convention is the "Remote Procedure Call", or RPC. The basic idea behind remote procedure calls is that a process (program) running on one computer can "call", using standard procedure calling semantics, another routine that executes on a different computer. A message-passing mechanism, based on DECnet, is used to transfer parameters between the caller and the called routine. This system can be used for communications between VMS, MicroVMS, and VAXELN computers.

Each control system computer, VAX/VMS, MicroVMS, or VAXELN, will eventually have a process called a Data-System Server. The data-system-server process, using the RPC interface, will service data-system requests to read data or give commands from remote computers. For example, a program running in the Polarized Injector MicroVMS system could not only get local CAMAC data, but could read RICE data from ACCR, issue commands to a serial CAMAC device on the IC MicroVMS system, and read a digital voltmeter on the TR VAXELN computer. The program would use standard data system subroutine calls and device names. The programmer writing the program need not know what computer the devices are ultimately accessed from. The data system will transparently handle the translation from mnemonic device name to hardware device access. Prototype data system servers are now running on several of our VMS and VAXELN remote computers.

## Future Possibilities

A control system is very much like a living organism, it continuously changes and grows throughout its lifetime. Now that we have finished the first phase of the LAMPF Control System upgrade, we can begin serious work on the next phase. This phase will be more evolutionary in its nature than the previous one. We plan to enhance the performance and responsiveness of the system, and gradually add new functions, while maintaining the basic software structure of the current system. The control system will continue to evolve towards a distributed system, and away from the centralized master/slave structure of the old SEL 840. Figure 3 shows what the LAMPF Control System might look like in three or four years.

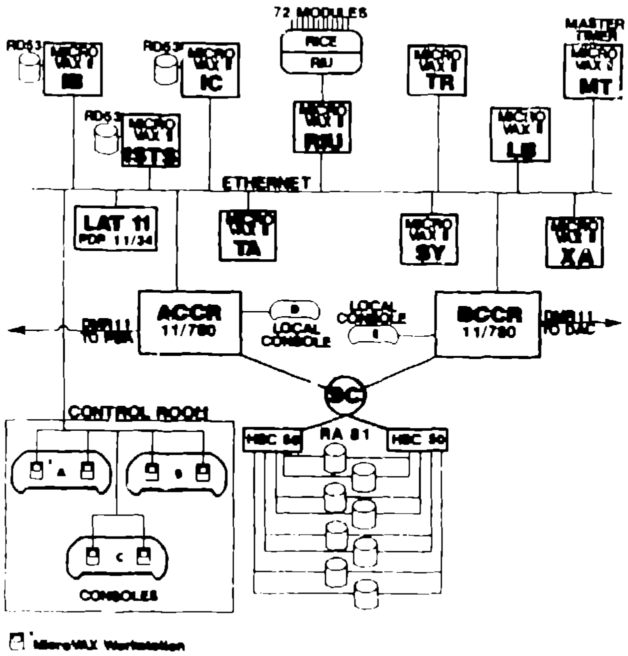


Figure 3 - LAMPF Control System in 1990?

## Disk Storage

We are planning to buy three more RA81 disks this year, and another next year. This will allow us to scrap the four RP06 local disks. These four disks have probably been responsible for half our maintenance problems over the last two years. With eight RA81 disks we can set up four of the disks online with full volume shadowing. This will give us transparent online recovery from the loss of any single disk or disk controller.

## New Remotes

We plan to replace the last two remaining PDP 11/10 computers (SY,XA) with standard VAXELN systems this year. This will also allow us to remove the NET11 gateway computer, and eliminate one more operating system (RSX-11M-PLUS). We will probably add another MicroVMS injector control system for H-, called IB, this year as well.

## More Horse Power

One of the disappointments of the current control system has been the inability to significantly improve the responsiveness of the control system over the old SEL 840. The current system does many more things than the old SEL 840, it's more stable (does not crash), and it is much more flexible than the old system. Unfortunately, it is often not any faster from the operator's point of view. Program development can also be very slow on BCCR during times of heavy usage. When we analyze system performance, it is very clear that the primary bottleneck on both ACCR and BCCR is a lack of sufficient CPU power. The great advantage that the current system has over the SEL 840 is that now there are several paths we can take to significantly increase system performance.

- Upgrade VAX 11/780 computers to VAX 11/785s. This would increase the available CPU power on each machine by about 50%, for a total increase of one VAX 11/780 equivalent. The hardware cost would be about $180,000. The software costs would be zero. The current LCS system should run without modification on the VAX 11/785s.

- Replace one or both of the VAX 11/780 computers with VAX 8600 or VAX 8650 computers. A VAX 8600 is about four times as powerful as a VAX 11/780. A VAX 8650 is about six times as powerful. For hardware costs of $300,000 to $900,000 we could get CPU increases of from three to ten VAX 11/780 equivalents. The software costs would again be zero.

- Install a MicroVAX in each operator console, keeping the same console hardware, and use both VAX 11/780s as disk servers, and for software development. If we installed one of the new MicroVAX IIIs in each of the three full operator consoles we could increase CPU power by the equivalent of between six and nine VAX 11/780s for hardware costs of between $100,000 and $200,000. This would require VMS support for mixed Ethernet and CI disk clusters, which is expected with version 5.0 of VMS. Access to the RICE system over Ethernet would be required, as would some software changes to the LAMPF Control System.

- A variation of the previous upgrade would be to replace the MicroVAX computers with MicroVAX workstations equipped with high precision color graphics scopes. We could then use multiple windows on the color graphics scopes to replace the color CRT, touch panels, and graphics terminals on the current operator consoles. We would probably have to keep the knobs on each console. We would like to prototype a system like this on one of the MicroVMS control systems. The new H- control system is a likely candidate.

We are actively investigating all these solutions. In the long run we are almost certain to go to one or more MicroVAXes at each operator console. This appears to be the most cost-effective hardware solution. It offers a simple path for continued growth, either through more powerful MicroVAX computers, more MicroVAX computers per console, or by adding consoles. This would also give us a distributed control system with multiple computers, each with its own full or partial console. In an emergency, any of the consoles (control computers) could run the control system by itself. This upgrade path requires some changes to the control system software in order to better support a more fully distributed control system. In the short run we also might upgrade the current 11/780 computers, particularly if we could get an attractive enough price on a used VAX 11/785, or 86XX.

## Graphics Enhancements

The current system uses standard graphics terminals driven through RS232 ports at 19.2 Kbaud. Each operator console has three graphics terminals. Any Tektronix 4014 compatible terminal can be used. We currently use Modgraph GX-1000, and Retrographics VT640 terminals. The graphics software used is a local modification to the National Center for Atmospheric Research (NCAR) software package.

We can increase graphics performance in two ways. One is by decreasing the wall-clock time it takes to plot a given graph. The second is to decrease the CPU time required to plot a given graph. From the operator's viewpoint, the most important time is the wall-clock time it takes to plot a graph. The most important factor in decreasing wall-clock times for our graphics system is the speed at which the graphics terminals will plot. We are already driving our current scopes as fast as they will go. The VT640 can only plot at about 4 Kbaud. The GX-1000 can plot at about 10 Kbaud. There are Tektronix 4014 compatible terminals that can plot at close to the 19.2 Kbaud line speed of our existing RS232 ports. We are looking into replacing the current graphics terminals with these faster scopes. We can probably do even better by replacing our graphics terminals with MicroVAX workstations. This would also fit in with plans to increase CPU power for the control system and adopting a new operator console format.

Any increase in plotting rates will also increase our CPU requirements for plotting. We are investigating both increasing the efficiency of the NCAR graphics package by better tuning it for our specific needs, and acquiring a new, more efficient graphics package.

## RIU/RICE Enhancements

RICE (Remote Instrumentation and Control Equipment) is a locally designed, distributed, module-oriented hardware system. RICE provides access to nintey percent of the devices accessed by the control system. Each RICE module has its own ADC and command-and-control electronics. It can independently take data or issue commands for the devices controlled by that module. Each RICE module can control a maximum of 144 binary channels (1 bit of information) and 128 analog channels (12 bits of information). Most modules control less. The RICE modules (there are 72 today) are interfaced to the computer through the Rice Interface Unit or RIU. RICE only supplies data on command from the RIU. The RIU can request data from a single module, or from all modules simultaneously. Currently access to the RIU is through the RIU11 gateway computer. The LAMPF Control System defines three types of data: timed, untimed, and non-RF. Timed data is taken at a fixed offset within a specified 8.33-ms beam pulse. Untimed data can be taken on any beam pulse at any time. Non-RF data can be taken on any beam pulse, but must be taken at a time during the beam pulse when RF power is off. In theory, a RICE unit can read a 12-bit data word every 400 microseconds. In practice, the RIU11 can probably do one timed, and one or two untimed, or non-RF data takes every beam pulse. The data takes could be for one module, or for all modules.

We are investigating two separate upgrades for the RIU/RICE system. We hope to eventually do both. The first is to replace the PDP 11/73 RIU11 with a MicroVAX II or III, interfaced to the control system through Ethernet. This would give any control computer on the Ethernet direct access to RICE data. With the increased power of the MicroVAX we should be able to improve performance, and optimize access to RICE data in several ways. The removal of the RIU11 will eliminate the last PDP 11, and the last RSX-11M system from the LCS. We hope to have the RIU MicroVAX ready for accelerator startup in 1988, probably using the current RIU/RICE hardware. Once this is done, we can follow the "console VAX" upgrade path to increase control system responsiveness.

The second upgrade for the RIU/RICE system would involve a redesign and modernization of the RIU/RICE hardware (originally designed in 1969). One option we are considering is to have each RICE module continuously read all the devices under its control. With modernized electronics and ADCs we think we can read each device in a module between 20 and 40 times a second, and maintain the latest value for each device in local memory. Untimed or non-RF data requests could then be satisfied with the last data read for a device. The RICE upgrade would be coupled with a redesign of the RIU, probably using a CAMAC based system. This would also require extensive modifications to the software for the MicroVAX RIU computer, and possibly some modifications to the LCS data system. If this upgrade is finally approved, it is probably several years away.

## Operator Console Enhancements

A standard LAMPF operators console has one color CRT (not a graphics scope), two VT100 based Carrol touch panels, three Tektronix 4014 compatible graphics terminals, and six knobs. The color CRT and knobs are interfaced to the control computers through CAMAC. The touch panels and graphics scopes are interfaced through RS232 ports running at 19.2 Kbaud.

One upgrade we are looking at is to replace the color CRT, graphics terminals, and touch panels with one or more MicroVAX workstations. This may also be done as part of a CPU and graphics upgrade. We already have a MicroVAX II/GPX which we hope to use to prototype such a system. In the short run we will probably just emulate the current interfaces, using the multiple window capability of the workstations to setup color CRT windows, graphics windows, and touch panel windows. This will allow existing applications to run without modification. In the long run we hope to establish a new operator interface that takes full advantage of the color-graphics workstation hardware and software capabilities. One of the big questions that we need to answer is how many application programs can practically be run on a workstation's 19 inch color-graphics scope at one time without the operators getting in each others way. It is not unusual to have four or five application programs running at one console at the same time. We will probably need at least two workstations per console.

## Integration With Proton Storage Ring Control System

The Proton Storage Ring (PSR) came on line at LAMPF in April of 1985. The control system was designed and built by Accelerator Technology division staff. The control system uses a MicrVAX II control computer, a VAX 11/750 for software development, and a network of LSI 11/23's for real time data aquisition and control. All data aquisition is through CAMAC. In 1986 support for the control system was turned over to MP division, and we began looking at ways to integrate the two control systems. At this time it is neither practical or necessary to rewrite any significant part of the two systems. Both work well and do the job they were designed for. What we hope to do is encourage the two systems to evolve towards a common form over the next several years. Our immediate plans are modest:

- Setup a standard software interface on both control systems to allow them to mutually access accelerator data from the other system.
- Use a standard naming convention for all accelerator hardware.
- Establish a standard operator interface for both systems. The staff for both control systems is looking at replacing their current

operator consoles with MicroVAX-based workstations. When, or if, this happens we will try to establish a common "standard operator interface" for both systems.

## Applying Artificial Intelligence Technology to Accelerator Controls

In 1986 we began to look seriously at using Artificial Intelligence techniques to assist in trouble shooting and tuning the LAMPF beam lines. At that time we committed one staff member to investigate and develop AI applications full-time. We purchased a MicroVAX II/GPX with 16 Mbytes of memory and 200 Mbytes of disk storage. In addition we purchased software licenses for Lucid Common Lisp and Intellicorp KEE (Knowledge Engineering Environment). The first applications we are investigating are the use of "Expert Systems" to help with tuning and/or debugging beam line failures.

The controls section is responsible for coordinating efforts to get the beam back online in the event of a beam-interrupting failure. Often-times this process is slowed by the absence of the person with the most knowledge on the area that failed. An expert system that captures unique knowledge may be a good way to ensure that the best "expert" assists in solving every failure. The problems with tuning are similar. The pool of people well versed in tuning the various portions of the accelerator is extremely limited. Often there is only one person per area. An expert tune advisor could document knowledge, remove some of the demands on the experts, and reduce the time it takes to complete the tuning process. We are now working on two prototype systems, one to help tune the first part of the H+ beam line, and the other to troubleshoot the NET11 and remote computer systems.

## Summary

The first phase of the LAMPF Control System upgrade has been completed. In January of 1987 the SEL 840 was rolled out the door of the computer room. The new control system has been used to tune and run the accelerator over the last year without any significant problems. We are now planning for the next phase of the control-system upgrade. This will be an evolutionary modification of the control system to enhance performance and responsiveness, increase reliability, and add new functions as they are required. The control system will continue to evolve towards a fully distributed system, and away from the master/slave structure of the original SEL 840 system.

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